Chapter 2
Investigation and Selection of Materials

2-1. Introduction

During the investigations for a civil works structure that incorporates concrete, it is necessary to assess the availability and suitability of the materials needed to manufacture concrete with qualities meeting the structural and durability requirements. Materials involved include cementitious materials, fine aggregate, coarse aggregate, water for mixing and curing, and chemical admixtures. These investigations will result in a separate DM or a portion of a DM, in accordance with Appendix C.

2-2. Cementitious Materials

a. General. The goal of the investigation of cementitious materials should be to determine the suitability and availability of the various types of cement, pozzolan, and ground granulated blast-furnace (GGBF) slag for the structures involved and to select necessary options that may be needed with the available aggregates. In cases where types or quantities of available cementitious materials are unusually limited, it may be necessary to consider altered structural shapes, changing the types of structure, altered construction sequence, imported aggregates, or other means of achieving an economical, serviceable structure.

b. Types. The following types of cementitious material should be considered when selecting the materials:

(1) Portland cement. Portland cement and air-entraining portland cement are described in American Society for Testing and Materials (ASTM) C 150 (CRD-C 201).

(2) Blended hydraulic cement. The types of blended hydraulic cements are described in ASTM C 595 (CRD-C 203). ASTM Type I (PM) shall not be used; reference paragraph 4-3b(7) of this manual.

(3) Pozzolan. Coal fly ash and natural pozzolan are classified and defined in ASTM C 618 (CRD-C 255).

(4) GGBF slag. GGBF slag is described in ASTM C 989 (CRD-C 205).

* Test methods cited in this manner are from the American Society for Testing and Materials *Annual Book of ASTM Standards* (ASTM 1992) and from *Handbook of Concrete and Cement* (U.S. Army Engineer Waterways Experiment Station (USAEWES) 1949), respectively.

(5) Other hydraulic cements.

(a) Expansive hydraulic cement. Expansive hydraulic cements are described in ASTM C 845 (CRD-C 204).

(b) Calcium-aluminate cement. Calcium-aluminate cements (also called high-alumina cement) are characterized by a rapid strength gain, high resistance to sulfate attack, resistance to acid attack, and resistance to high temperatures. However, strength is lost at mildly elevated temperatures (e.g. >85 °F) in the presence of moisture. This negative feature makes calcium-aluminate cement impractical for most construction. It is used predominantly in the manufacture of refractory materials.

(c) Proprietary high early-strength cements. Cements are available that gain strength very rapidly, sometimes reaching compressive strengths of several thousand pounds per square in. (psi) in a few hours. These cements are marketed under various brand names. They are often not widely available, and the cost is much higher than portland cement. The extremely rapid strength gain makes them particularly suitable for pavement patching.

(6) Silica fume. Silica fume is a pozzolan. It is a byproduct of silicon and ferro-silicon alloy production. Silica fume usually contains about 90 percent SiO_2 in microscopic particles in the range of 0.1 to 0.2 µm. These properties make it an efficient filler as well as a very reactive pozzolan. Silica fume combined with a high-range
∗ water reducer is used in very high-strength concrete. Silica fume is described in ASTM C1240 (CRD-C270). Detailed information can be found in paragraphs 2-2*d*(5) and 10-10.∗

(7) Air-entraining portland cement. Air-entraining portland cement is only allowed for use on structures covered by the specifications for "Concrete for Minor Structures," CW-03307. Air-entraining admixtures are used on all other Corps civil works structures since this allows the air content to be closely controlled and varied if need be.

c. Selection of cementitious materials.

(1) General. The selection of one or several suitable cementitious materials for a concrete structure depends on the exposure conditions, the type of structure, the characteristics of the aggregate, availability of the cementitious material, and the method of construction.

(2) Type of structure. The type of structure, i.e. mass or structural, provides an indication of the category of

concrete that the structure may contain. Mass concrete is defined as any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cementitious materials and attendant volume change to minimize cracking. A gravity dam and a navigation lock are examples of massive structures. Structural concrete is defined as concrete which will normally be placed in reinforced structural elements such as beams, columns, walls, and slabs that have dimensions such that heat generation is not a problem. Many features of a structure will fall between the two extremes of being either strictly massive or structural, and the designer will need to decide if measures to limit or mitigate the heat generation will be required. For example, reinforced walls and slabs of 4- to 6-ft thickness in a pumping station that contains 3,000- to 5,000-psi concrete would probably generate sufficient heat that measures should be taken to limit either the peak temperature of the concrete or the rate at which heat is lost from the concrete after the peak temperature is reached. The factors that affect the amount of heat that is generated and the peak temperature that the concrete will reach are the amount and type of cementitious materials in the concrete, the size of the placement, and the initial placing temperature.

(a) Table 2-1 lists cementitious materials that should be investigated for availability and suitability, according to the type of structure. Other more specialized cementitious materials, such as Type V portland cement or proprietary high-early strength cement, should be investigated if needed.

(b) Specification details. Type II cement is described by ASTM C 150 (CRD-C 201) as a cement for use when moderate sulfate resistance or moderate heat of hydration is desired. The heat-of-hydration part of this description requires that the 70-calorie/gram optional limit be specified. Many Type II cements evolve heat at rates comparable to those of Type I cements. The chemical requirement which is in ASTM C 150 for the purpose of limiting heats of hydration is not a satisfactory means of assuring reduced heat of hydration and should not be used. Neither Type IV portland cement nor Type P portland-pozzolan cement are generally available at the present time. Both also exhibit very low rates of strength gain. These characteristics should be addressed in the concrete materials DM prior to specifying either type. ASTM C 989 (CRD-C 205) includes a provision for three grades of GGBF slag, grade 120, which contributes to the fastest strength development, grade 100 which is an intermediate grade, and grade 80 which contributes least to strength development. However, at present, only grade 120 is available. Generally, if other grades were available, grade 80, 100, or 120 should be considered for use in mass concrete, and grades 100 and 120 should be considered for use in structural concrete.

(3) Other requirements.

(a) General. The investigation of cementitious materials must include an assessment of the impact on cost and availability of special requirements or options. Provisions that limit the heat of hydration, provide sulfate resistance, limit the alkali content, or control false set should be invoked based on a demonstrated need for cement having these characteristics.

(b) Sulfate exposures. Precautions against the potentially harmful effects of sulfate will be specified when concrete is to be exposed to seawater or the concentration of water-soluble sulfate (SO_4) in soil or in fresh water that will be in contact with the concrete (as determined by CRD-C 403 and 408) is greater than 0.10 percent or 150 parts per million (ppm,) respectively. Concentrations higher than these will be classified as representing *moderate* or *severe* potential exposures according to the criteria shown in Table 2-2. The precautions to be specified will vary with the availability and anticipated costs of materials and with other factors. Where moderate attack is to be resisted, moderate sulfate-resisting cement (Type II, Type III with the optional 8 percent limit on C_3A invoked, Type IP(MS), Type IS(MS), or Type P(MS)) should be specified. In seawater where no greater precautions than moderate are needed, the 8-percent limit on C_3A may be increased to 10 percent if the water-cement ratio (w/c) of the concrete is kept below 0.45 by mass and the concrete will be permanently submerged in seawater. If moderate sulfate-resisting cement is not economically available, concrete that is resistant to moderate attack may be made by using Type I cement having not more than 10 percent C_3A or Types IS or IP which contain an adequate amount of suitable Class F pozzolan or slag or to which additional Class F pozzolan or slag is added. Performance tests must be conducted to determine the suitability of any substitutes for sulfate-resistant cement. If straight portland cement is proposed, the test method is described in ASTM C 452 (CRD-C 232). If a blend of portland cement and pozzolan or a blended hydraulic cement is proposed, the test method is ASTM C 1012 (CRD-C 211). Where severe attack is to be resisted, highly sulfate-resistant cement (Type V, Type III with 5 percent limit on C_3A) should be specified and used unless problems of cost or availability are encountered, in which case other materials as outlined above should be taken. Additional information may be obtained from American Concrete Institute (ACI) 201.2R.

Table 2-1
Guide for Selection of Cementitious Materials According to Type Structure

Cementitious Material	Mass Concrete	Structural Concrete
Portland cement:		
Type I		X
Type II	X	X
Type II with heat of hydration 70 cal/g or less	X	X
Type I with pozzolan		X
Type II with pozzolan	X	X
Type I with GGBF slag		X
Type II with GGBF slag	X	X
Type III		X
Type IV	X	
Blended hydraulic cements:		
Type IS(MH)	X	X
Type IS		X
Type IP(MH)	X	X
Type IP		X
Type P	X	
Type P(LH)	X	
Type I(SM)		X
Type I(SM), (MH)	X	
Type S, with Type I or Type II Portland cement	X	

Table 2-2
Guide for Determining Sulfate Exposure Condition

Exposure condition	SO_4 concentration, Fresh water	SO_4 concentration, Soil, %
Moderate	150 - 1,500 ppm	0.10 - 0.20
Severe	>1,500 ppm	>0.20

(c) False set. False set is one type of the abnormal premature stiffening of cement within a few minutes of mixing with water. Remixing of the concrete after a few minutes of maintaining the mixer at rest or a longer initial mixing time will restore the plasticity of the mixture, and it will then set and gain strength normally. False set normally does not occur when ready-mix trucks are used to transport concrete because of the length of the mixing cycle. When such lengthy mixing or a remix step, as described above, is impractical, then the optional requirement limiting false set in ASTM C 150 (CRD-C 201) should be invoked. When premature stiffening cannot be overcome by additional mixing, it is probably "flash set" due to inadequate retardation of the cement during manufacture.

(d) Cement-admixture interaction. Some cement-admixture combinations show no tendency to cause early stiffening when tested according to ASTM C 451 (CRD-C 259) but will cause early stiffening when used with some water-reducing admixtures. The phenomenon can be detected by testing the cement and admixture proposed for use according to ASTM C 451. Also see paragraph 2-5 on chemical admixtures.

(e) Alkali reactivity. The potential for deleterious reactivity of the alkalies in the cement with the aggregate should be evaluated as outlined in Appendixes D and E of this manual. If the aggregates are potentially reactive, paragraph D-6 presents options, including disapproval of the aggregate source, use of low-alkali cements, or use of GGBF slag or pozzolans.

(f) Heat of hydration. The heat of hydration should be limited in those cases where thermal strains induced on cooling of the concrete are likely to exceed the strain capacity of the concrete in the structure. This is accomplished by specifying the available option for limiting the heat of hydration for Type II portland cement or using Type IV cement, if available. For blended hydraulic cements, the heat of hydration is limited by specifying the suffix (MH) for Type IS, I(SM), IP, S, and (LH) for Type P. The replacement of a portion of the portland cement or in some cases blended hydraulic cement with a pozzolan or GGBF slag should always be considered. The heat generation of each proposed cement type and each combination of cement and pozzolan or slag should be determined. The amount of heat generated should be equal to or less than the amount generated by the Type II with heat-of-hydration option which is also normally specified.

(4) Requirements for use of other hydraulic cements.

(a) Expansive hydraulic cement. Expansive cements have been used in floor slabs, in the top lifts of some lock walls, and in the lining slab of spillway channels to reduce shrinkage cracking. The applications have generally been accomplished in closely controlled situations and after extensive investigation. Additional reinforcement is usually required to control the expansion. Since the use of expansive cements in water-control structures is far from common, its proposed use will require a comprehensive investigation to be included in the concrete-materials DM.

(b) High-alumina cement. High-alumina cement is not normally used in civil works structures and should be considered only in those locations which justify its added cost and after investigating the possible effects of its tendency to lose strength when exposed to heat and moisture. Its use should be preceded by a comprehensive investigation which is made a part of the concrete materials DM.

(c) Proprietary high early-strength cements. Cements that develop high strength within a few hours are often considered for use in cold weather applications or for repair applications, or both, that are required to bear load soon after finishing. The investigation that precedes its use should determine availability and the characteristics of the available material. The results of the investigation should be included in the concrete materials DM.

(5) Pozzolans. The classes of pozzolans most likely to be available are classes F and C fly ash and silica fume. Class N may be considered at those sites where a source of natural pozzolan is available.

(a) Regulations governing use of fly ash. The Solid Waste Disposal Act, Section 6002, as amended by the Resource Conservation and Recovery Act of 1976, requires all agencies using Federal funds in construction to allow the use of fly ash in the concrete unless such use can be shown to be technically improper. The basis of this regulation is both energy savings and waste disposal, since most fly ash in use today is the result of the burning of coal for electrical power.

(b) General. The use of pozzolan should be considered coincident with the consideration of the types of available cements. Portland cement to be used alone should always be considered in the specifications as well as blended hydraulic cements or the combination of portland cement with slag cement or pozzolan unless one or the latter is determined to be technically improper. Classes F and C fly ash are generally accepted on all Corps of Engineers' (CE) civil works projects, and their use should be allowed in all specifications unless there are technical reasons not to do so.

(c) Class F pozzolan. Class F pozzolan is a fly ash usually obtained from burning anthracite or bituminous coal and is the class of fly ash that has been most commonly used to date. It must contain at least 70.0 percent of $Si0_2 + Al_20_3 + Fe_20_3$ by chemical analysis.

(d) Class C pozzolan. Class C pozzolan is a fly ash that is usually obtained from the burning of lignite or subbituminous coal. It must contain at least 50.0 percent of $Si0_2 + Al_20_3 + Fe_20_3$.

(e) Other considerations. Class C fly ashes often contain considerably more alkalies than do Class F fly ashes. However, when use of either class in applications where alkali-aggregate reaction is likely, the optional available alkali requirement of ASTM C 618 (CRD-C 255) should be specified. Use of Class F fly ash in replacement of portland cement results in reduction of heat of hydration of the cementitious materials at early ages. Use of Class C fly ash in the same proportions usually results in substantially less reduction in heat of hydration. An analysis of the importance of this effect should be made if Class C fly ash is being considered for use in a mass concrete application. See paragraph 3-2b, "Thermal Studies." Class F fly ash generally increases resistance to sulfate attack. However, if the portland cement is of high C_3A content, the amount of improvement may not be sufficient so that the combined cementitious materials are equivalent to a Type II or a Type V portland cement. This can be determined by testing according to ASTM C 1012 (CRD-C 211). Class C fly ashes are quite variable in their performance in sulfate environments, and their performance should always be verified by testing with the portland cement intended for use. Both Class F and Class C fly ashes have been found to delay for initial and final set. This retarding action should be taken into consideration if important to the structure. Most Class C and Class F fly ashes are capable of reducing the expansion from the alkali-silica reaction. Use of an effective fly ash may eliminate the need to specify low-alkali cement when a reactive aggregate is used. The effectiveness of the fly ash must be verified by ASTM C 441 (CRD-C 257). For additional information, see Appendixes D and E.

(f) Class N pozzolan. Class N is raw or calcined natural pozzolans such as some diatomaceous earths, opaline cherts, tuffs, and volcanic ashes such as pumicite.

(g) Silica fume. Silica fume is a pozzolan. It is a byproduct of the manufacture of silicon or silicon alloys. The material is considerably more expensive than other pozzolans. Properties of silica fume vary with the type of silicon or silicon alloy produced, but in general, a silica fume is a very finely divided product and consequently is used in concrete in different proportions and for different applications than are the more conventional pozzolans discussed in the previous paragraphs. Applications for which silica fume is used are in the production of concrete having very high strengths, high abrasion resistance, very low permeability, and increased aggregate bond strength. However, certain precautions should be taken when specifying silica-fume concretes. Use of silica fume produces a sticky paste and an increased water demand for equal slump. These characteristics are normally counteracted by using high-range water-reducing admixtures (HRWRA) to achieve the required slump. This combination, together with an air-entraining admixture, may cause a coarse air-void system. The higher water demand for silica-fume concrete greatly reduces or eliminates bleeding, which in turn tends to increase the likelihood of plastic shrinkage cracking. Therefore, steps should be taken as early as possible to minimize moisture loss, and the curing period should be increased over that required for conventional concrete. For additional information, see paragraph 10-10i.

d. Availability investigation of cementitious materials.

(1) General. Following the investigation outlined previously in paragraph 2-1c to determine the technical requirements of the cementitious materials for a project, it is necessary to assess availability of those materials in the project area. Technical requirements to use a certain type or kind of cementitious material to assure long-term durability and serviceability of the structure shall not be compromised because of the cost of obtaining the material. All cementitious materials should be furnished by the Contractor. The contract specifications should allow the Contractor maximum flexibility to provide cementitious materials that meet the technical requirements for the project. The investigation should cover an area sufficient to provide at least two sources of each cementitious material to provide price competition. An estimate of the cost per ton of each material delivered to the project should be secured from each producer. The key objective of the availability investigation is to ensure that materials meeting the technical requirements can be obtained by the Contractor.

(2) Portland cement and blended hydraulic cements. The availability of the technically acceptable portland

cement and blended hydraulic cement types must be investigated prior to listing materials in the DM or the contract specifications. Any optional physical or chemical requirements from ASTM C 150 (CRD-C 201) or ASTM C 595 (CRD-C 203) that are to be invoked by the designer must be considered during the investigation. For example, Type II cement or Type IP blended hydraulic cement may be readily available in the project area, but when the heat-of-hydration option is invoked from ASTM C 150 for portland cement or from ASTM C 595 for blended hydraulic cement, the availability may be severely reduced. Producers in the project area should be queried about their current production and also about their ability and willingness to produce material that meets any optional physical or chemical requirements that the designer deems necessary.

(3) Pozzolans. The availability of technically acceptable pozzolans, both natural pozzolans and fly ashes, must be investigated prior to listing materials in the contract specifications. Normally, only commercial sources of natural pozzolan and fly ash that are economically viable for use on the project will need to be investigated. Undeveloped sources of natural pozzolans should not be investigated unless there are no other sources of pozzolan available. CECW-EG should be contacted for guidance in evaluating an undeveloped source of natural pozzolan. The availability investigation should include any optional chemical or physical options from ASTM 618 (CRD-C 255) that the designer needs to invoke for technical reasons. Producers in the project area should be queried about their production and material properties and also about their ability and willingness to produce material that meets any optional requirements that the designer deems necessary. It should be stressed that the uniformity requirement in ASTM 618 will be required.

(4) GGBF slag. The availability of technically acceptable GGBF slag must be investigated prior to listing it in the contract specifications. Availability is presently limited and only Grade 120 material is being produced. GGBF slag must meet the requirements of ASTM C 989 (CRD-C 205).

(5) Silica fume. Silica fume is generally available only from national distributors as a proprietary material. It
* is a relatively expensive material. Therefore, it is rarely used in mass concrete structures but more likely in structural concrete and shotcrete applications. When specifying silica fume, the optional requirement of specific surface area in ASTM C 1240 Table 4 should be invoked in all cases. The optional Table 2 in ASTM C 1240 should be used only if low alkali cement is required. The uniformity requirement in Table 4 should be invoked when concrete is air-entrained. The sulfate resistance expansion requirement in Table 4 need not be included except in areas where sulfate attack is expected. All other optional requirements in Table 4 need not be specified unless past experiences or environment conditions justify these tests. *

2-3. Aggregates

a. General. One of the most important factors in establishing the quality and economy of concrete is a determination of the quality and quantity of aggregates available to the project. Preliminary investigation to determine potential aggregate sources should be performed during the feasibility phase, and detailed investigations should be performed during the PED prior to issuance of P&S's. All sources investigated during the PED should be documented in the appropriate DM, and those sources found capable of producing aggregates of suitable quality should be listed for the Contractor's information in the specifications. Ideally, the sources investigated should be within a few miles of the project; however, depending on the quality of aggregates required and the availability of transportation, aggregates may be transported a considerable distance. Not all sources within a certain distance of a project need be investigated, but representative sources from various kinds of sources in the vicinity must be evaluated to establish the quality of aggregates that can be produced. The investigation should be comprehensive enough to assure that more than one source of each aggregate type and size is available to the Contractor. The decision of whether or not to investigate a potential source should not be based on the grading of materials currently stockpiled at the source but should be based on determining the quality of the aggregate from the source or formation. The Contractor/producer should be given the opportunity during construction to adjust his processing to meet the grading specified. The investigation will result in a list of aggregate qualities that are required for the project and an acceptance limit for each quality. The aggregate qualities and their respective limits must be documented in a DM and will be used in preparation of specifications for the project.

(1) Sources of aggregate (Government or commercial). The decision to investigate a Government source or only commercial sources is based on appraisal of the economic feasibility of an onsite source when compared to commercial sources that contain aggregate of adequate quality and that are within economic hauling distance of the project. The appraisal should also consider the environmental consequences of opening and restoring the Government site.

If a Government source is investigated, it will be owned or controlled by the Government and will be made available to the Contractor for the production of aggregate. The presence of a Government source does not preclude the investigation of commercial sources that appear to be economically feasible. All sources investigated will be documented in the appropriate DM.

(2) Minor structures. For minor structural projects, the source of aggregate need not be listed since a quality requirement is specified by reference to ASTM C 33 (CRD-C 133). Before specifications are issued, the availability of aggregate meeting these requirements should be determined. If none are economically available to the project, then the specifications should be altered to allow the use of the specification under which most of the satisfactory aggregate in the area is produced, whether that be a state or local specification.

b. Availability investigation.

(1) General. The objectives of the availability investigation are to determine the required aggregate quality for the project, the quality of the aggregate available to the project, and that sufficient quantity of the required quality is available. The required aggregate quality is stated in the appropriate DM as a list of aggregate properties and their respective acceptance test limits. Preliminary investigations to determine the potential sources and the required aggregate quality shall be performed during the feasibility phase and the results documented in the engineering appendix to the feasibility report. During the PED, field explorations and sampling and testing of aggregates should be initiated based on the work previously completed in the feasibility report. This activity should be continued with an increasingly expanded scope through the completion of the concrete materials DM. If satisfactory Technical Memorandum No. 6-370, "Test Data, Concrete Aggregates and Riprap Stone in Continental United States and Alaska" (USAEWES 1953), data are available and less than 5 years old, it will not be necessary to repeat the sampling and testing of those sources for which such data are available. See Appendix C for further guidance on the scope of the investigation.

(2) Service records. Service records can be of great value in establishing the quality of an aggregate where reliable information on the materials used to produce the in situ concrete, construction procedures, and job control are available. The service record must be of sufficient time to assure that possible deleterious processes have had time to manifest themselves and the existing structure must be in the same environment that the proposed structure will be subjected to. Photographs should be used to document the condition of the in situ concrete.

(3) Field exploration and sampling of undeveloped sources. In undeveloped potential quarries, field explorations should consist of a general pattern of core borings arranged to reveal the characteristic variations and quality of material within the deposit. Representative portions of the cores should be logged in detail and should be selected for laboratory testing in accordance with CRD-C 100. In addition to the small holes, large calyx drill holes should be used to obtain large samples for processing into aggregate similar to that required for the project, unless a test quarry or test pit is to be opened. Additional information on the exploration of undeveloped quarry sources is available in EM 1110-1-1804, "Geotechnical Investigations," and EM 1110-2-2302, "Construction with Large Stone," and these references should be consulted prior to undertaking an investigation. During PED, for a source of crushed stone for a large project, a test quarry should be opened and samples tested to assure that the required quality is available. In the case of undeveloped alluvial deposits, explorations should consist of a sufficient number of test pits, trenches, and holes to indicate characteristic variations in quality and quantity of material in the deposit. Grading of materials in alluvial deposits should be determined to establish grading trends within the deposits. Representative samples of materials should be selected for laboratory testing in accordance with CRD-C 100. Procedures for making subsurface explorations are described in EM 1110-1-1804, "Geotechnical Investigations."

(4) Field exploration and sampling of developed sources. In commercial sources, a thorough geologic evaluation should be made of the deposit from which the raw materials are being obtained to determine the extent of the deposit and whether or not material remaining in the deposit may be expected to be essentially the same as that recovered from the source at the time of the examinations. In quarries and mines, working faces should be examined, logged, sampled, photographed, and when considered necessary, mapped. When available, results of and samples from subsurface explorations performed by the owner should be examined and evaluated. Where no subsurface information is available and proper appraisal cannot be made without it, arrangements should be made with the owner to conduct the necessary subsurface explorations. The primary source of samples for quality evaluation testing should be from material produced at the time of the investigation. These samples should be supplemented by samples from working faces and subsurface explorations. All samples should be taken in accordance with CRD-C 100.

(5) Testing potential aggregate sources. During the PED phase, there should be sufficient testing to define the quality of aggregates available within an economic hauling distance of the project. The sampling and testing program should be designed to evaluate geologic formations, deposits, strata, or rock type available to the project. It is not necessary to sample and test all producers within the economic hauling distance of the project.

(6) Evaluating aggregate qualities.

(a) Significance of test results. Aggregate quality cannot be measured by fixed numbers from laboratory test results only. These results should be used as indicators of quality rather than as positive numerical measures of quality. An aggregate may still be considered acceptable for a given project even though a portion of the test results fall outside the conventional limits found in reference standards such as ASTM C 33 (CRD-C 133). Results of individual tests should be considered and the final judgment should be based on overall performance, including service records where available. The cost of obtaining aggregates of the quality necessary to assure durability during the life of the project should not be a factor in establishing the required quality. The incremental cost of obtaining quality aggregates during initial construction is always less than the cost of repairs if concrete deteriorates during the service life of the project due to aggregate deficiencies. Detailed discussions of the interpretation of aggregate test data can be found in ACI 221R and EM 1110-2-2302, "Construction with Large Stone." See also the discussion in paragraph 2-3b(9)(b), "Acceptance Criteria."

(b) Petrographic examination (ASTM C 295 (CRD-C 127)). Results of a petrographic examination should be used both for assessing the suitability of materials and for determining what laboratory tests may be necessary to evaluate the suitability of materials for use as concrete aggregate. Petrographic examination is performed for two purposes: (1) lithologic and mineralogic identification and classification and (2) determination of composition, physical, and chemical characteristics. From this examination, a description of material should be written and a preliminary estimate of the general quality of the material should be made. It is possible to identify the presence of constituents that are capable of reacting with the alkalies in cement from petrographic examination. When such constituents are identified, other investigations, including the Quick Chemical Test (ASTM C 289 (CRD-C 128)) or Mortar-Bar Test (ASTM C 227 (CRD-C 123)), or both, should be performed to determine their potential reactive effects. Table 2-3 lists the testing property, testing method, and comments regarding the testing.

(c) Specific gravity (ASTM C 127; ASTM C 128). Specific gravity of aggregates is necessary for calculating the mass for a desired volume of material. It has no clearly defined significance as a measure of suitability of material for use as concrete aggregate. Aggregates with specific gravity below 2.4 are usually suspected of being potentially unsound and, thus, not suited for use in the exposed portions of hydraulic structures in moderate-to-severe exposures. However, these materials may still be used if their performance in freezing-and-thawing tests is acceptable. Low specific gravity has been indicative of poor quality in porous chert gravel aggregates having high absorption. Therefore, it may be necessary to set a limit on the permissible amount of material lighter than a given specific gravity when selecting chert gravel aggregates for use in hydraulic structures in moderate or severe environment. The specific gravity limit and the permissible amount lighter than the limit should be established on the basis of results of laboratory freezing-and-thawing tests.

(d) Absorption (ASTM C 127; ASTM C 128). Absorption is determined primarily as an aid in estimating amounts of water in aggregates for laboratory and field control of amount of mixing water used in the concrete. Absorption data are generally believed to be somewhat indicative of the probable influence of aggregates on the durability of concrete exposed to freezing and thawing when subject to critical saturation. However, test results have indicated that this premise must be used with caution in assessing the quality of material. High absorption in aggregates may be an indication of potential high shrinkage in concrete and may need further investigation. However, absorption alone should not be considered significant as a measure of suitability of a material for use as concrete aggregate.

(e) Organic impurities (ASTM C 87; ASTM C 40). The test for presence of organic impurities should be used primarily as warning that objectionable amounts of organic impurities may be present in the aggregates. Objectional amounts of organic matter will usually show "darker than No. 3" in the ASTM C 40 test. Primary dependence should be placed on the mortar strength tests as a basis for judging whether or not objectionable amounts of organic impurities are present in natural fine aggregate. Natural fine aggregate showing the presence of organic matter and producing mortar strength of less than 95 percent of those produced by the same aggregate after washing with sodium hydroxide to remove organic matter should not be selected for use unless it is evident that the material can be adequately processed to remove impurities.

Table 2-3
Standard Procedures for Obtaining Information on Aggregate Quality During the Preconstruction Engineering and Design Phase

Testing Property	Testing Method*	Comments
Composition and identification	ASTM C 295	This petrographic examination is recommended for all aggregate evaluation and should be the basis for the determination of other procedures required.
Specific gravity and absorption	ASTM C 127 ASTM C 128	Density will affect the density of concrete. In general, higher absorption of coarse aggregate may indicate less F/T resistance (CRD-C 107 and 108, respectively).
Organic impurities	ASTM C 40 ASTM C 87	Too much impurity will affect the concrete strength. ASTM C 87 (CRD-C 116) should be performed if there are objectionable amounts of organic impurities (CRD-C 121 and 116, respectively).
Soft constituents	CRD-C 141 CRD-C 130	Soft materials in fine aggregate will affect concrete strength and workability. Soft particles in coarse aggregate will affect the bonding with cement.
Clay lumps and friable particles	ASTM C 142	Clay lumps and friable particles will affect concrete strength and workability (CRD-C 142).
Lightweight particles	ASTM C 123	Lightweight particles will affect the density of concrete (CRD-C 122).
Particle shape	ASTM D 4791 CRD-C 120 ASTM D 3398	Particle shape will affect the density and workability of concrete (CRD-C 129).
Soundness of aggregate in concrete	CRD-C 114 (ASTM C 666)	Results are directly related to the F/T resistance of concrete.
Frost resistance	ASTM C 682	This test may be valuable in evaluating frost resistance of coarse aggregate in concrete (CRD-C 115).
Abrasion loss	ASTM C 131 ASTM C 535	These tests may indicate the degree of resistance to degrading of coarse aggregates during handling and mixing (CRD-C 117 and 145, respectively).
Specific heat	CRD-C 124	Needed for thermal analysis.
Linear thermal expansion	CRD-C 125 CRD-C 126	Needed for thermal analysis. Aggregates with very high or low thermal coefficient may require further investigation.
Alkali-silica reactivity	ASTM C 289 ASTM C 227	Perform these tests if there is an indication of potential alkali-silica reactivity (CRD-C 128 and 123, respectively). (See Appendix D for details.)
Alkali-carbonate reactivity	ASTM C 586	Perform this test if there is an indication of potential alkali-carbonate reactivity (CRD-C 146). (See Appendix E for details.)
Concrete making properties	ASTM C 39 and others	Perform these tests as needed to determine the suitability of aggregates for high strength concrete (CRD-C 14).

*Test methods cited are from the American Society for Testing and Materials *Annual Book of ASTM Standards* (ASTM Annual) and from Department of the Army, Corps of Engineers, *Handbook of Concrete and Cement* (USAEWES 1949).

(f) Soft constituents, clay lumps, and lightweight particles (ASTM C 123 (CRD-C 122); ASTM C 851(CRD-C 130); CRD-C 141; ASTM C 142 (CRD-C 142)). Results of tests for soft particles, clay lumps, and lightweight pieces are largely used as information that may have a bearing on or assist in rationalizing results of other tests such as the accelerated weathering test or the strength properties of the concrete. The tests may sometimes be useful in determining whether or not processing of the material to remove the undesirable constituents is feasible when they occur in proportions which make the material unfit for use without removal.

(g) Particle shape (ASTM D 4791; CRD-C 120; ASTM D 3398 (CRD-C 129)). The test for flat and elongated particles provides information on particle shape of aggregates. Excessive amounts of flat or elongated particles, or both, in aggregates will severely affect the water demand and finishability. In mass concrete structures, the amount of flat or elongated particles, or both, at a 3:1 length-to-width (L/W) or width-to-thickness (W/T) ratio is limited to 25 percent in any size group of coarse aggregate. Although there is no requirement in structural concrete, the effect of more than 25 percent flat or elongated particles should be examined during the design process. The results of the examination should be discussed in the appropriate design memorandum. The maximum L/W or W/T ratio, when testing in accordance with ASTM D 4791 is normally 3:1.

(h) Soundness of aggregate by freezing and thawing in concrete (CRD-C 114). This test is similar to ASTM C 666 (CRD-C 20), procedure A, except that a standard concrete mixture is used to evaluate the effect of aggregates on freezing-and-thawing resistance. This test is more severe than the aggregates will experience in service. Nevertheless, it provides an important measurement in relative aggregate quality in freezing-and-thawing resistance and is the best means now available for judging the relative effect of aggregates on frost resistance. In general, however, aggregates are rated in relative quality by this test as shown in Table 2-4. *This table also provides the recommended DFE value based upon the project location, and expected exposure. For the purpose of simplicity the weathering region (Fig. I) in ASTM C 33 is used as an indicator of the potential freeze and thaw exposure for the area. The engineer may adjust this requirement if there is data available indicating that the situation is different from the one shown in ASTM C 33 Fig. 1.* Although the test is reasonably repeatable, it is not possible to prevent small differences in the size and distribution of air voids caused by different cements and air-entraining admixtures and possible other factors; thus, it is not possible to judge accurately the quality of protection of cement paste in each instance even though air content for all tests is kept within a small range. Therefore, it is not unusual to find that these differences will cause variations in test results of sufficient magnitude from two separate tests on essentially identical aggregate samples to shift the quality rating from one level to another. The test also has limitations on the size of aggregates that can be tested. The maximum size of aggregate used in the tests is ~~190~~ *19.0* mm (3/4 in.), whereas aggregate up to 150 mm (6 in.) is frequently used in mass concrete. Therefore, the test is of limited value when the +19.0-mm (+3/4-in.) aggregate varies substantially in characteristics from that finer than 19.0 mm (3/4 in.). In spite of its limitations, the test provides an excellent means of evaluating the relative quality of most materials and results of the test should be given prime consideration in selecting aggregate quality requirements. Where the laboratory freezing-and-thawing test is considered inadequate as a basis for judging the quality of the aggregates, particularly for sizes larger than 19.0 mm (3/4 in.), concrete made with the larger sizes may be exposed at Treat Island, Maine, where the Corps of Engineers' severe-weathering exposure station is located to determine the durability of the specimens. The decision to expose specimens at Treat Island should be made early in the investigation so that they may be exposed for at least two winters. To determine durability, 2-ft cube specimens cast from air-entrained concrete containing the desired maximum size of aggregate should be used. In an average period of 2 years, specimens are subjected to at least 250 cycles of freezing and thawing. If no marked reduction in pulse velocity has occurred and no distress is visually evident in the period, the aggregates may be considered to be of good to excellent quality.

(i) Frost-resistance test (ASTM C 682 (CRD-C 115)). This dilation test provides another indication of aggregate quality in freezing-and-thawing resistance when used in concrete. It measures the dilation of a specimen under slow freezing-and-thawing cycles and is similar to ASTM C 671 (CRD-C 40) except a standard air-entrained concrete mixture is used. In air-entrained concrete in which the paste is adequately protected against frost action, the quality of the aggregate is the main factor that contributes to deterioration. Results of this test are very sensitive to the moisture condition of aggregate and concrete and should be compared carefully with the conditions in the field.

(j) Sulfate soundness (ASTM C 88 (CRD-C 137)). In the past, ASTM C 88, "Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate," has been used quite often. This test is the only one which is performed on aggregate directly by soaking material in sulfate solution to simulate the effect of increase in volume of water changing to ice or freezing in the aggregate pores. ASTM C 88 is not recommended due to its poor correlation with the actual service performance of concrete.

(k) Abrasion loss (ASTM C 131 (CRD-C 117); ASTM C 535 (CRD-C 145)). If a material performs well in other tests, particularly resistance to freezing and thawing, high

Table 2-4
Concrete Durability Factors for Assessing Aggregate Durability.

DFE Range*	Over 75	50-75	25-50	Less than 25
Weathering Region per ASTM C33 Fig. I	*Severe*	*Moderate*	*Negligible*	*No F/T cycle*
Quality Rating	Excellent	Good	Fair	Poor

*DFE = Durability factor (based on relative dynamic modulus of elasticity).

abrasion loss may not be significant. It should be recognized, however, that a material having high abrasion loss will tend to degrade in handling and that excessive grinding may occur with such materials during mixing. These aspects should be investigated as a basis for evaluating the acceptability of a material. It should be noted that there is no relationship between abrasion loss from these tests and concrete abrasion or durability in service.

(1) Specific heat and thermal expansion (CRD-C 124, CRD-C 125, CRD-C 126). The results of these tests are properties of the aggregate and are needed when performing thermal analysis.

(m) Alkali-aggregate reactivity (ASTM C 227; ASTM C 289; ASTM C 586 (CRD-C 123, 128, and 146, respectively)). Criteria for recognizing potentially deleterious constituents in aggregate and for evaluating potential alkali-silica and alkali-carbonate reactivity are given in Appendixes D and E, respectively. If aggregates containing reactive constituents are to be used, the problem then becomes one of identifying the reactive constituents and determining the conditions under which the available aggregates may be used. Where the reactive constituents can be positively determined to occur in such small proportions as to be innocuous, an aggregate, if otherwise of suitable quality, may be used without special precautions. Where the reactive constituents occur in such proportions that they are potentially deleteriously reactive, it will be necessary to use low-alkali cement or an effective pozzolan, or both, with the aggregate. If the requirement of low-alkali cement would impose serious difficulties of cement procurement or excessive increase in cost, consideration should be given to the use of portland blast-furnace slag cement (a blend of portland cement and slag), Portland-pozzolan cement, cement with GGBF slag, or cement with a pozzolan, or both, that will prevent excessive reaction even when high alkali-cement is used. When consideration is given to the use of any of these materials in lieu of low-alkali cement, mortar-bar tests should be conducted to verify that the potentially deleterious expansion will be reduced to meet the criteria in Appendix D or E. If petrographic examination determines the presence of potentially reactive materials in excess of the limits given in Appendix D, mortar-bar tests, ASTM C 227 shall be performed. If the petrographic examination determines the presence of strained quartz in excess of the limit given in Appendix D, the high- temperature mortar-bar test shall be performed.

(n) Concrete making properties (ASTM C 39 (CRD-C 14)). When it is desired to select aggregate for concrete with strengths of 6,000 psi or greater, some otherwise acceptable aggregates may not be suitable. Concrete-strength specimens, made from concrete using the aggregate being evaluated and of the required slump and air contents, should be tested at various cement factors, w/c, and including any required chemical admixtures. If the required strength cannot be obtained with a reasonable slump, air content, cement factor, and chemical admixture(s), the aggregate should not be considered as acceptable for the high strength concrete. Materials that are satisfactory in other respects usually have acceptable strength and bonding characteristics. A complete discussion of high-strength concrete may be found in ACI 363R.

(o) Service performance. The performance of aggregates in service in structures is considered the best general evidence of aggregate quality when dependable records are available and the exposure conditions are similar. Service records are usually of greater usefulness when commercial sources of aggregate are being investigated. Service performance, however, must be considered with caution. Poor condition of a structure is not necessarily evidence of poor quality aggregate. There are many factors which may contribute to the poor performance of the concrete in service. However, except where a slow acting reactive aggregate is involved, a structure in good condition is always an indication that the aggregates are of adequate quality for concrete exposed to similar conditions.

(7) Nominal maximum size aggregate. In general, it is economical to use the largest aggregate compatible with placing conditions. Table 2-5 provides guidance in making the selection. On projects not involving large quantities of

Table 2-5
Nominal Maximum Size of Aggregate Recommended for Various Types of Construction

Features	Nominal Maximum Sizes
Section 7-1/2 in. or less in width or slabs 4 in. or less in thickness. Heavily reinforced floor and roof slabs. Parapets, corbels, and all sections where space is limited and surface appearance is important. High-strength concrete	19.0 mm (3/4 in.)
Section 7-1/2 in. wide and in which the clear distance between reinforcement bars is at least 2-1/4 in. and slabs at least 4 in. thick.	37.5 mm (1-1/2 in.)
Unreinforced sections over 12 in. wide and reinforced sections over 18 in. wide, in which the clear distance between reinforcement bars is over 4-1/2 in. Piers, walls, baffles, and stilling basin floor slabs in which satisfactory placement of 6-in. aggregate concrete cannot be accomplished even though reinforcement spacing would permit the use of large aggregate. Slabs 10 in. or greater in thickness.	75 mm (3 in.)
Massive sections of dams and retaining walls; ogee crests, piers, walls, and baffles in which clear distance between reinforcement bars is at least 9 in. and for which suitable provision is made for placing concrete containing the large sizes of aggregate without producing rock pockets or other undesirable results. Slabs 24 in. or greater in thickness.	150 mm (6 in.)

concrete, a careful study should be made of the economy of large aggregates. The use of large aggregates reduces the cement content, but it increases plant costs because provision must be made for the handling of more individual sizes. Nominal maximum size aggregate (NMSA), 150 mm (6 in.) or even 75 mm (3 in.), should not be specified if the volume of concrete is so small that savings in cement will not pay for increased plant expenses. When an economic study indicates the use of 75-mm (3-in.) or 150-mm (6-in.) NMSA concrete results in comparable costs and the additional cement required in the 75-mm (3-in.) NMSA concrete does not detrimentally affect the concrete, optional bidding schedules should be used. The additional cementitious quantities of 40 lb/cu yd of concrete is typical when 75-mm (3-in.) NMSA concrete is used in lieu of 150-mm (6-in.) NMSA concrete.

(8) Fine aggregate grading requirements. During the course of the aggregate investigations, the grading of the available fine aggregate from all sources should be determined and compared to the anticipated project specifications. The project grading requirements will depend on the guide specification selected for the project. If the most readily available materials do not meet the applicable grading requirements and the processing required to bring the material into the specified grading limits results in increased costs, consideration should be given to substituting a state or local specification that is determined to cover the fine aggregate grading available at commercial sources in the project area. The substitution should be based on the determination that concrete meeting the project requirements can be produced using the locally available fine aggregate. If a large mass concrete structure is involved which will be built to the requirements of CW-03305, "Guide Specification for Mass Concrete," using an onsite fine aggregate source, the decision to waive the grading requirements will also be based on the results of the processibility study, which includes estimates of waste and laboratory data that show that concrete can be produced using the fine aggregate grading proposed which meets all the project requirements. The study should include an economic evaluation which shows, clearly, that the increased

cost of cement and finishing, when a nonstandard grading is used, will be more than offset by the savings in processing and waste reduction. Particular attention should be given to the increased workability gained by use of an optimum amount of material finer than the 300-µm (No. 50) and 150 µm (No. 100) sieves. Many studies have shown that it is cost effective to blend in a fine "admix" sand in this size range if the available sand is deficient in these sizes. The limits to be permitted on the proposed grading should also be stated. Manufactured fine aggregate has a tendency for the dust that is generated during the crushing and sizing process to cling to the larger particles and to clump or ball up when exposed to moisture. The amount of dust can be significant and can cause problems during construction. The dust may not come loose or break up during sieving per ASTM C 136 (dry grading), and it may be difficult to accurately monitor the grading. The dust can also cause the moisture content of stockpiled material to be higher and more variable than expected; this in turn can result in difficulties controlling the batch masses and slump of the concrete. Excessive dust can cause the water demand of concrete to increase with resultant loss of strength. Therefore, when manufactured sand is allowed in project specifications, the designer should invoke the optional requirements in CW 03305, "Guide Specification for Mass Concrete," that will limit the amount of material (dust) passing the 75-µm (No. 200) sieve and that will require washing the material during grading testing (ASTM C 117 (CRD-C 105)). The option may also be invoked for natural fine aggregate at the designer's discretion.

(9) Required tests and test limits.

(a) General. For all civil works concrete construction projects except those for which the guide specification CW-03307, "Concrete for Minor Structures," is used, a list of required quality tests and test limits must be established and inserted in the specifications. Required tests and test limits must be site-specific for the project area, the general rule being that the best locally available aggregates are to be used. This list of tests and test limits may be specific for only one project or, according to the amount of diversity of the geology and the resulting rock types in an area, could be district- or division-wide lists. On some projects where, for instance, both river gravels and crushed stone are included in the list of sources, a set of tests and test limits would be required for the gravel and a slightly different set of tests and test limits would be required for the crushed stone.

(b) Acceptance criteria. Establishing test limits for aggregate quality for a project is very complex and should be done with great care and deliberation. Limits established for a specific test for one rock type at one project would not necessarily assure durable concrete for a different rock type at the same project or for the same rock type at a different project. For example, a minimum density of 2.52 for coarse aggregate at a specific project may be adequate for some types of chert or river gravel but would not be adequate for crushed limestone. The selection of which tests to specify for indicating the quality of aggregate and the respective acceptance limits for each test should come after completion of all testing for each source or formation and should include due consideration of service records. The acceptance limits should be set recognizing that all test results have some scatter and that most ASTM (CRD) test methods include precision and bias statements. EM 1110-2-2302, "Construction with Large Stone," contains an excellent discussion on setting acceptance criteria and should be consulted for further guidance. The district materials engineer should work closely with the division office when establishing acceptance criteria for a project so that close coordination between adjacent districts and between adjacent divisions can be maintained for a given source or formation.

(10) Aggregate processing study. A processing study should be considered for any government-furnished source. The processing study should be conducted by a division laboratory having the capability of processing large (1- to 2-ton) samples. The sample should be processed to meet the grading and particle-shape requirements of the project by crushing and screening as necessary. The processing study will provide information on which to base estimates of waste and also will provide an indication of the potential for the development of flat and elongated particles to an extent which will influence the workability and cement requirements of the concrete. For large mass concrete jobs, a test quarry may be required. This is usually done as a separate construction contract to qualified private companies skilled in blasting (if a quarry operation) and skilled in processing rock or gravel deposits to meet concrete aggregate gradings. In this more elaborate type of investigation, the processing of the raw material would be accomplished onsite, instead of in the division laboratory. Information to be required would include optimum blasting patterns, quality of each rock stratum, amount of waste, particle shape, and the ability of the deposit to be processed into the required gradings.

(11) Location of government-furnished quarry or pit. The objective should be to define clearly one or more areas which will be described in the specifications and shown in the contract drawings. The purpose will be to provide the

bidders with information that will make it possible for them to estimate accurately the cost of producing the aggregate and subsequently to provide information to the contractor for use in planning his aggregate production operations. Explorations should be carefully logged and the information included in the contract drawings. Materials recovered during these and previous explorations should be preserved and made available for inspection by the bidders and by the Contractor for use in planning his work. Where zones or layers exist that are unsuitable, they should be specifically identified and the listing of the source should note the unsuitability of those zones or layers.

2-4. Water for Mixing and Curing

a. General. The most readily available water sources at the project site should be investigated during the PED phase for suitability for mixing and curing water. Also, water that will be in contact with the completed structure should be tested to determine if it contains a concentration of chemicals which may attack the hardened concrete. For additional information, see the Portland Cement Association's "Design and Control of Concrete Mixtures" (Kosmatka and Panarese 1988).

b. Mixing water. To determine if water from sources other than a municipal water supply is suitable for mixing, it should be investigated during the PED phase in accordance with CRD-C 400 (USAEWES 1949). If contamination by silt or a deleterious material exists, samples should be taken when contamination is the greatest.

c. Curing water. Water for curing must not contain harmful chemical concentrations and it must not contain organic materials such as tannic acid or iron compounds which will cause staining. If certain water sources around the project area have a potential for staining and others are nonstaining, the staining sources should be eliminated from use by the specifications and the acceptable sources noted so that unsightly staining may be prevented. However, the Contractor is responsible for providing surfaces free of stain after curing. This is a preferable approach to attempting to remove the staining with often unsatisfactory results. Curing water should be tested in accordance with CRD-C 400.

2-5. Chemical Admixtures

a. General. The chemical admixtures that may be used in concrete on Corps projects are air-entraining admixtures (ASTM C 260), accelerating admixtures, water-reducing admixtures, retarding admixtures, water-reducing and retarding admixtures, water-reducing and accelerating admixtures, high-range water-reducing admixtures, and high-range water-reducing and retarding admixtures. All of the latter are discussed in ASTM C 494 (CRD-C 87). Chemical admixtures to produce flowing concrete are discussed in ASTM C 1017 (CRD-C 88). Other admixtures may be used when their use on the project results in improved quality or economy. When admixtures are considered during the PED phase to provide special concrete properties, trial batches with materials representative of those that will be used for the project should be proportioned and tested. The effects of the admixture on the concrete properties and the required dosage rate should be reported in the concrete materials DM. Admixtures proposed for use during construction should be checked with trial batches, using the actual project materials in the Division laboratory. However, if the source of the concrete is a ready-mix plant with a recent history of use of the admixture with project materials, trial batches need not be required. In some instances, adverse reactions may occur between admixtures or between admixtures and cement or water. Admixtures should not be mixed together prior to batching, but each should be batched separately. A detailed discussion of chemical admixtures for concrete is given in ACI 212.3R.

b. Air-entraining admixtures. Air-entraining admixtures (AEA's) are organic materials which entrain small air bubbles into concrete. These bubbles become a part of the cement paste that binds the aggregates together in the hardened concrete. Air entrainment improves the workability of concrete, reduces bleeding and segregation, and most importantly improves the frost resistance of concrete. Air entrainment is essential to ensure the durability of concrete that will become critically saturated with water and then exposed to freezing-and-thawing conditions. However, air entrainment only protects the paste fraction of the concrete. It does not protect concrete from deterioration caused by nonfrost-resistant aggregates.

(1) Policy. All civil works concrete should be air entrained with an appropriate AEA. Any exceptions to this practice must be submitted to CECW-EG for approval.

(2) Strength loss. Even if freezing-and-thawing conditions are not prevalent, concrete should be air entrained because of the benefits imparted in other ways. The presence of entrained air results in an improvement in the workability of concrete at the same water content. To maintain a given slump, a reduction in the water content of up to 15 percent can be made depending upon the air and cement contents. The reduction in the water content results in a lower w/c, which will offset some or all of the loss in strength due to the presence of the entrained air, depending on the cement content; calculations indicate that at about

300 lb of cement per cubic yard, an increase in air content will be balanced by a sufficient decrease in w/c at constant slump to maintain constant strength.

(3) Bleeding. Air-entrained concrete is less susceptible to bleeding. When successive lifts of concrete are to be placed, more effort will be required for horizontal lift joint cleanup if bleeding is excessive. A considerable reduction in bleeding by proper air entrainment is usually a major benefit. Air entrainment also imparts a buoyant action to the cement and aggregate particles which helps to prevent segregation. Even though it is an aid against segregation, it cannot prevent segregation of concretes having poorly graded aggregates, ones that are excessively lean or wet, or ones that are improperly transported or placed.

(4) Batching AEA. An AEA should be added to the mixing water prior to its introduction into other concrete materials. If other admixtures are also used, the AEA should be added to the concrete mixer separately and not intermixed with the other admixtures.

(5) Dosage. Many variables will determine the exact dosage of an AEA needed to achieve the proper air-void system in a concrete mixture. In general, larger amounts of AEA will produce higher air contents in a concrete mixture. However, there is no direct relationship between the dosage rate of a given AEA and the air content that is produced.

(6) Effects of water content on air content. Air content will usually increase or decrease as the water content of a mixture is increased or decreased. An increase in the water content in the concrete results in a more fluid mixture into which the air bubbles can be more easily incorporated by the mixing action. For example, a slump increase of about 3 in. can cause an increase in air content of about 1 percent with the same dosage of an AEA.

(7) Effects of fine aggregate grading on air content. Air is more easily entrained in concretes having higher percentages of fine aggregate. The fine aggregates provide interstices that can contain the air bubbles, especially the sizes from about 600 µm (No. 30) to the 150 µm (No. 100). Concretes made with fine aggregates deficient in particles of these sizes can require larger amounts of AEA's to achieve the desired air content, especially in lean concretes. Conversely, concretes made with an excess of finely divided materials can also require larger amounts of AEA's to achieve the desired air content. Very fine sand fractions (150 µm (No. 100) and smaller), fly ash , and high cement contents have caused a reduction in air contents. Fly ashes which have high loss on ignition cause an especially large reduction in the air content. Concrete made with a Type III cement can require up to 50 percent more AEA's than concrete made with a Type I cement.

(8) Effects of temperature on air content. The temperature of the concrete has a direct effect upon the air content of the concrete at given AEA dosage. A lower temperature results in a higher air content, and vice versa. Therefore, if the concrete temperature changes significantly during production of a particular concrete mixture, it is likely that the amount of AEA must be adjusted accordingly to maintain the desired air content.

(9) Effect of other admixtures on air content. Less AEA is generally required to entrain air in concrete when water-reducing or retarding admixtures are also used. The required amount of AEA may be as much as 50 percent less, especially when lignosulfonate-based chemical admixtures are used because these materials also have a moderate air-entraining capacity.

(10) Effect of mixing action on air content. Effective mixing action is necessary to produce air-entrained concrete. The amount of entrained air will vary with the type and physical condition of the mixer, the mixing speed, and the amount of concrete being mixed. It is more difficult to entrain air in concrete using a severely worn mixer or one that has an excessive amount of hardened concrete buildup on the blades or in the drum. Air contents can also decrease if the mixer is loaded above its rated capacity. Studies have shown that air contents generally increase with mixing up to about 15 min. Thereafter, additional mixing leads to a decrease in air content, especially for low-slump concretes. Any transporting technique that will continue to agitate the concrete, such as pumping or conveying, usually decreases the air content.

c. Accelerating admixture. Accelerating admixtures are classified by ASTM C 494 as Type C, accelerating, or Type E, water-reducing and accelerating. Accelerating admixtures accelerate the setting time or early strength development of concrete or both. Initial and final setting times must be accelerated by a minimum of 1 hr, and 3-day compressive strengths must be increased by a minimum of 25 percent in order for an accelerating admixture to comply with the requirements of ASTM C 494 (CRD-C 87).

(1) Uses. CW-03301 and CW-03305 provide for the use of nonchloride accelerating admixtures subject to the approval of the Contracting officer. The use of a nonchloride accelerating admixture may be approved when concrete is being placed in cold weather to partially offset the retarding effect of the lower temperatures. Its use permits earlier finishing of slabs and reduces form removal

delays. The use of an accelerating admixture does not permit a reduction of specified curing and protection periods.

(2) Nonchloride admixtures. Several nonchloride organic and inorganic compounds, such as calcium formate, calcium nitrite, and triethanolamine, are available as accelerators. However, experience and published research on these admixtures are limited. The available data suggest that none of the nonchloride accelerating admixtures are as powerful an accelerator as calcium chloride at equal dosages. However, adequate acceleration can usually be attained with a nonchloride accelerating admixture if the proper dosage is used. Nonchloride accelerators usually come in liquid form and should be added at the mixer with a portion of the mixing water at a dosage rate recommended by the manufacturer. They should be added to the concrete separately and not mixed with other admixtures. In some instances, adverse reactions occur between admixtures which can decrease their effectiveness.

(3) Effect on fresh concrete properties. Type C accelerating admixtures have no significant effect on the initial workability or air content of a concrete mixture; however, the setting time, heat evolution, and strength development are affected. Concretes containing an accelerating admixture can have a more rapid slump loss, especially concretes having a high cement content. The bleeding of a concrete mixture is generally reduced when an accelerating admixture is used.

(4) Effect on hardened concrete properties. Properties of hardened concretes containing an accelerating admixture are generally increased at early ages but may be decreased at later ages. Compressive and flexural strengths will be higher at early ages but can be lower than those of plain concrete at later ages. Both creep and drying shrinkage may increase. Concretes containing accelerators may be less resistant to aggressive environments, especially at later ages. The passive layer of protection at the concrete-steel interface does not appear to be attacked by nonchloride accelerators. Proper curing procedures are essential when concrete contains an accelerating admixture.

(5) Other methods of accelerating strength development. Frequently, the acceleration of setting time and early strength development can be obtained by other means, such as (a) using a Type III portland cement, (b) using additional cement, (c) lowering the pozzolan content, (d) warming water and aggregates, (e) improving curing and protection, or (f) some combination of these. In some cases, the use of an accelerator is the most convenient and economical method of achieving the desired results; however, convenience and economics should not take precedence over durability considerations.

d. Retarding admixtures. Retarding admixtures are materials which cause a delay in initial and final setting times. However, retarding admixtures do not reduce the rate of slump loss. Retarding admixtures are classified by ASTM C 494 (CRD-C 87) as Type B, retarding, or Type D, water-reducing and retarding. They must retard the initial setting time by a minimum of 1 hr and the final setting time by a minimum of 3-1/2 hr. Setting times of concrete made with a portland cement-pozzolan blend will typically be retarded more than when portland cement alone is used. The pozzolan often has a retarding action.

(1) General uses. By using the proper dosage of a retarding admixture, the setting time of a mixture can be extended so as to avoid cold joints and allow for proper finishing. A change in temperature could require an adjustment in the dosage of retarder to maintain the desired setting time. Retarding admixtures can be beneficial in hot weather, when long hauling distances are unavoidable, or anytime extended working times are desirable. The time between screeding and troweling operations of concrete slabs is extended when retarding admixtures are used. This can be particularly beneficial in hot weather; however, unless proper precautions are taken, such as the use of sunscreens and wind screens, the surface may dry prematurely and create a crust on the surface. Under these conditions, careful attention to curing and protection is required to obtain a uniform hardening in the entire concrete slab. Retarding admixtures based on hydroxylated carboxylic acids and their salts are beneficial in concrete used in flatwork construction during hot weather since they induce bleeding and, therefore, aid in the prevention of a premature drying of the top surface.

(2) Dosage. The dosage of admixture recommended by the manufacturer should be used unless experience or results of trial batches indicate otherwise. High temperatures may require higher dosages of retarding admixtures; however, overdosage can cause excessive retardation requiring longer curing times and delays in form removal. The degree of excessive retardation could be from a few hours to a few days. However, an accidental overdosage of a retarding admixture does not adversely affect the later age properties of a concrete if the concrete is cured properly and the forms are not removed until sufficient strength has been attained. Research has shown that a higher dosage of retarding admixtures is needed when used with portland cements that have high C_3A and C_3S contents, as well as a high alkali content. Therefore, to achieve the same effects, a larger dosage of retarding admixture will probably be required if

a Type I portland cement is used than will be required if a Type II, low-alkali portland cement is used.

(3) Batching. Retarding admixtures should be added to the mixing water prior to its introduction into other concrete materials. If other admixtures are also used, the retarding admixture should be added to the concrete mixture separately and not mixed with the other admixtures. In some instances, adverse reactions occur between admixtures which can decrease their effectiveness.

(4) Effect on strength. When retarding admixtures are used in concrete, early-age compressive and flexural strength may be reduced. If a low dosage of admixture is used, the lower strengths may be evident for as few as 1 or 2 days. Greater degrees of retardation may cause the strengths to be lower for 3 to 7 days. However, in most cases there will be no retardation of strength development by 28-days age. Lower strengths may exist for a longer period of time if the concrete is made with a portland cement-pozzolan blend. At later ages, the strength of concrete made with a retarding admixture will usually be higher than that of concrete containing no retarding admixture.

e. Water-reducing admixtures. Water-reducing admixtures (WRA's) are organic materials which reduce the amount of mixing water required to impart a given workability to concrete. By definition, WRA's are required to provide a water reduction of at least 5 percent and are classified by ASTM C 494 (CRD-C 87) as Type A, water-reducing; Type D, water-reducing and retarding; or Type E, water-reducing and accelerating. They can be used to increase strength, increase workability, or reduce the cement content of a concrete mixture.

(1) Use in mass concrete. A WRA generally should not be allowed in lean mass concrete mixtures since neither high strength nor high slump are usually required from these mixtures. A reduction in the cement content permitted by the use of a WRA could result in the mixture having inadequate workability. This is especially true for mass concrete mixtures containing 37.5-mm (1-1/2-in.) or larger nominal maximum size aggregate.

(2) Dosage. The usual dosage rate for a WRA is between about 2 and 8 fl oz/100 lb of cementitious material. The appropriate amount will be determined by the brand of WRA being used as well as the combination of other concrete materials. Some WRA's meet ASTM C 494 (CRD-C 87) requirements for both Type A and Type D, depending upon the dosage rate used. These WRA's will usually react as a Type A at the lower limit of the recommended dosage range and as a Type D at the upper limit of the recommended dosage range.

(3) Use in hot or cool weather. A Type D WRA can be beneficial when working in hot weather, when long hauling times are involved, or anytime extended working times are desirable. However, the retarding effect increases the concrete setting time only. It does not slow the rate of slump loss. In fact, concretes containing either Type A, Type D, or Type E WRA generally lose slump at a faster rate than when a WRA is not used. A Type E WRA may be beneficial when working in cool temperatures or when higher earlier strengths are desired.

(4) Air entrainment. Most lignosulfonate WRA's will entrain air. However, the amount of entrained air will usually not be sufficient to provide adequate frost resistance. An AEA will be required in addition to the WRA, but the amount of AEA necessary may be as much as 50 percent less. WRA's based on other compounds generally do not entrain air but do enhance the air-entraining capability of AEA's.

(5) Bleeding. WRA's affect the rate and capacity of fresh concrete to bleed. Lignosulfonate WRA's reduce the bleeding rate and capacity while WRA's based on hydroxylated carboxylic acids and their salts increase the bleeding rate and capacity of a concrete mixture. A lignosulfonate WRA should be used with caution in concrete placed in slabs during hot weather. With little bleed water migrating to the surface, rapid surface drying could occur, leading to a crust on the concrete surface while the concrete underneath remains plastic. The potential for plastic shrinkage cracking is also greater. It is beneficial to induce bleeding under these ambient conditions. WRA's based on hydroxylated carboxylic acids and their salts will accomplish this objective.

f. High-range water-reducing admixtures ("superplasticizers"). High-range water-reducing admixtures (HRWRA's) are chemically different from normal WRA's and are capable of reducing water contents by as much as 30 percent without detrimentally affecting air content, bleeding, segregation, setting time, and hardened properties. By definition, HRWRA's are required to provide a water reduction of at least 12 percent and are classified by ASTM C 494 as Type F, high-range water-reducing, or Type G, high-range water-reducing and retarding. HRWRA's can be used to produce concrete having high workability for easy placement, high strength with normal workability, or combinations of the two. HRWRA's can also be used to produce flowing concrete as described by ASTM C 1017

(CRD-C 88). Additional information on flowing concrete may be found in paragraph 10-9.

(1) Effect on workability. Significantly higher compressive strengths are possible with the use of an HRWRA. Concrete can be produced having a lower w/c without the loss of workability that could occur with the use of WRA's. The increased workability made possible with an HRWRA permits easier placement of concrete in congested reinforcement and in areas where access is limited. HRWRA's are beneficial in concrete which is pumped or placed by tremie because they improve workability without a loss in cohesiveness. The dispersing action of HRWRA is effective on both portland cements and pozzolans. The ability of an HRWRA to increase the slump of concrete depends upon the chemical nature of the HRWRA, the dosage used, time of addition, initial slump, composition and amount of cement, and concrete temperature. Recommended dosages of HRWRA's are usually greater than those of WRA's. There are some limitations of HRWRA's that should be recognized. Under some conditions, concretes containing HRWRA's may exhibit a rapid slump loss as soon as 30 min after completion of mixing. Therefore, HRWRA's are often added to truck mixers at the job site to minimize placing and consolidation problems associated with concrete which stiffens rapidly.

(2) Effect on segregation and bleeding. When HRWRA's are used as water reducers, bleeding of the concrete is usually reduced. Segregation of the aggregates will not be a problem. When HRWRA's are used to produce flowing concrete, both bleeding and segregation can occur if precautions are not taken. Increasing the volume of sand in the mixture by 3 to 5 percent may be necessary. The dosage of HRWRA should be limited to the minimum amount necessary to produce the desired slump. An overdose can cause excessive bleeding and segregation. However, bleeding and segregation of a high-slump concrete is not as pronounced when the high slump is achieved through use of an HRWRA as would be the case if the high slump were achieved through the addition of extra water. Retempering once with an HRWRA is generally an acceptable practice.

(3) Effect on air entrainment. Some HRWRA's enhance the air-entraining capability of AEA's. However, HRWRA's can also facilitate the escape of air. Repeated dosing with an HRWRA can accentuate this effect. In addition to the rapid slump loss, a significant loss of air can occur.

(4) Effect on setting time. A Type F HRWRA has little effect upon setting times of concrete, while a Type G HRWRA retards the setting time. The usual dosage range for HRWRA is between about 10 and 30 fl oz/100 lb of cementitious materials. The appropriate amount will be determined by the type of HRWRA being used as well as the combination of other concrete materials and admixtures. Some HRWRA's meet ASTM C 494 requirements for both Type F and Type G, depending on the dosage rate used. These HRWRA's will usually react as a Type F at the lower end of the recommended dosage range and as a Type G at the upper end of the recommended dosage range. If one of these HRWRA's is being used at a low dosage, and it is desired to increase the dosage for additional water reduction, caution should be exercised. The higher dosage could cause undesirable retardation of concrete setting time and strength.

(5) Compatibility with other admixtures. HRWRA's are generally compatible with most other concrete admixtures. However, each admixture combination should be evaluated prior to being used. In particular, attention should be given to the air content and air-void system parameters. Appropriate durability tests should be performed depending on the environment to which the concrete will be subjected. When concrete containing an HRWRA is properly air entrained, it will be as durable as that without an HRWRA.

g. Antiwashout admixtures. In recent years a group of chemical admixtures known as antiwashout admixtures (AWA's) has been introduced into the concrete products market. ASTM standard specifications have not yet been developed for these admixtures. They are used to increase the cohesiveness of a concrete to prevent excessive washing out of cementitious materials when the concrete is placed underwater. A workability transformation occurs after several minutes of mixing, thereby causing the concrete to become very sticky. Present guide specifications do not include AWA's. The use of AWA's should be discussed in the appropriate DM.

(1) General. AWA's can be made from various organic and inorganic materials. The two materials most commonly marketed as AWA's are cellulose and gum. They act primarily by increasing the viscosity and the water retention of the cement paste. Both materials are very effective in increasing the washout resistance of a concrete mixture. The washout resistance depends upon the type and dosage of AWA, w/c, cement content, and other admixtures used. In general, the washout resistance increases with an increase of AWA, a decrease in w/c, and an increase in

cement content. The loss of cementitious materials due to washing is typically reduced by as much as 50 percent when concrete contains an AWA.

(2) Batching. AWA's based on cellulose are normally packaged in a powder form. They are usually added to the concrete mixer with the cement. AWA's based on gum may be packaged either as a powder or liquid. The powder should be put into solution with a portion of the mixing water prior to introduction into the concrete mixture. The liquid can be added with the mixing water.

(3) Air entrainment. AWA's based on cellulose tend to entrain air. In combination with some WRA's or HRWRA's, AWA's will entrain an excessive amount of air. When this occurs, an air-detraining admixture must be incorporated into the concrete mixture to reduce the air contents to acceptable levels. AWA's based on gum usually do not entrain air.

(4) Bleeding. Since AWA's increase the water retention of cement paste, virtually no bleeding occurs in concretes containing these admixtures. However, this would normally be of little concern in concrete placed underwater.

(5) Retardation. AWA's based on cellulose tend to retard the setting time of concrete. Larger dosages of these AWA's can retard concrete setting times significantly, in some cases up to 24 hr. If the delayed setting time poses problems with other construction operations, an accelerator can be used to partially offset the retardation. AWA's based on gum usually do not retard setting times as much as those based on cellulose.

(6) Compatibility. AWA's have little effect on compressive strengths of concrete. The amount of mixing water necessary for concrete made with an AWA is greater than would be necessary for concrete without an AWA. In many cases the amount of mixing water can be reduced with a WRA or an HRWRA. In fact, when concretes have w/c less than 0.50, the use of a WRA will probably be necessary. When the w/c is less than 0.40, the use of an HRWRA will be necessary to achieve the flowability necessary for an underwater placement. Cellulose-based AWA's and napthlene sulfonate-based HRWRA's are incompatible, and combinations of these should be avoided. Cellulose-based AWA's are generally compatible with other types of HRWRA's and most WRA's. Gum-based AWA's are generally compatible with most WRA's and HRWRA's.

(7) Dosage. The proper dosage of AWA's, WRA's, and HRWRA's, as well as the compatibility of these admixtures, must be determined in trial batches prior to the beginning of any concrete placement. The amount of an AWA necessary to achieve the desired washout resistance can vary considerably depending upon the concrete materials being used and their proportions. An excessive amount of AWA can render the concrete unworkable, while too little AWA will not provide adequate washout resistance. Follow the manufacturers recommendations for dosages and adjust as necessary in preliminary trial batches. Extreme caution should be exercised if it becomes necessary to adjust the dosage of either the AWA, WRA, or HRWRA after the actual placement begins. A small change in the dosage can result in a dramatic change in the workability and cohesiveness of the concrete. When the use of an AWA is specified, the services of a qualified manufacturer's technical representative should be required. The technical representative should be available during mixture proportioning studies and be onsite during concrete placement. The concrete mixture containing the AWA should be proportioned in the division laboratory if the mixture is government furnished or in an approved commercial laboratory if proportioning is a Contractor responsibility.

(8) Pumping. The cohesiveness imparted by an AWA actually improves the pumpability of concrete for distances up to approximately 150 ft. If the pumping distance exceeds 250 ft, pumping pressures will likely increase significantly. If the pumping pressures become excessive, the concrete mixture proportions must be adjusted by adding water or reducing the amount of the AWA, or the pump must be relocated to reduce the pumping distance. Adjusting the mixture proportions in this manner may reduce the concrete cohesiveness and cause it to be more susceptible to washout; therefore, relocating the pump, if possible is the preferable solution.

h. Extended set-control admixtures.

(1) General. These admixtures are relatively new to the commercial market and were developed to give the ready-mixed concrete producer maximum flexibility in controlling the rate of hydration of fresh concrete. They are typically marketed as a two-component system consisting of a very strong retarding admixture, sometimes referred to by the manufacturer as a stabilizer, and an accelerating admixture, sometimes labeled as an activator by the manufacturer. These admixtures allow the concrete producer to take advantage of severely retarded fresh concrete in several ways, including:

(a) Treating unhardened concrete which is returned to the plant with the stabilizer so that it can be kept in the unhardened state, or stabilized, in the truck mixer or holding hopper for several hours. When the concrete is needed, cement hydration is normally reactivated by combining freshly mixed concrete with it before sending it to the job site. Returned unhardened concrete may also be stabilized overnight or longer. In these cases, hydration of the cement in the stabilized concrete is typically reactivated by adding the activator and then combining the concrete with freshly mixed concrete before delivering it to the job site.

(b) Treating the freshly mixed concrete at the plant with the stabilizer so that hydration is retarded to the extent necessary for very long hauls. Typically, the duration of retardation is at least 1 or more hours, and use of the activator may or may not be necessary at the job site, depending on the dosage of stabilizer used.

(c) Stabilizing plastic concrete in a truck mixer which has experienced a mechanical breakdown or an unforeseen delay. In the event of a truck breakdown, the mixer drum must still be able to turn.

(d) Treating wash water from mixers with the stabilizing admixture to reduce the need for conventional wash water disposal methods and thereby mitigating the environmental concerns. Water consumption is also reduced. The stabilized wash water is then reused as mixing water in the concrete batched the next day or after the weekend.

(2) Stabilizer. The stabilizing admixture slows the rate of hydrate formation by tying up, or complexing, calcium ions on the surface of cement particles. It not only forms a protective barrier around the cement particles but also acts as a dispersant preventing hydrates from flocculating and setting. This protective barrier prevents initial set from occurring.

(3) Activator. The activating admixtures typically supplied with the extended-set admixture systems are nonchloride accelerating admixtures conforming to ASTM C 494, Type C (CRD-C 87).

(4) Effect on hardened properties. Few published data exist on the effects of extended set admixtures on the hardened properties of concrete. However, research indicates the use of a stabilizing admixture may cause finer and denser hydrates to form, which, in turn, appears to benefit physical properties of paste.

(5) Dosage. Extended-set control admixtures are usually delivered in liquid form. Because they are still relatively new to the concrete industry and because there are presently no standard specifications for them, their use should be permitted only after data are supplied by the concrete supplier that the fresh and hardened properties of the concrete anticipated for use will not be detrimentally affected. Manufacturer's technical representatives should work closely with the concrete producer to assure correct dosage rates are established for the particular concretes and field applications.

i. Antifreeze admixtures. A new group of chemical admixtures recently introduced into the concrete products market is known as antifreeze or freezing-protection admixtures. ASTM standard specifications have not yet been developed for these admixtures. These materials, which have been in use in the former USSR since the 1950's and more recently in Western Europe, are designed to depress the freezing point of mixing water and thereby allow concrete to gain strength in an environment below freezing without suffering the deleterious effects of ice formation. Concrete made with antifreeze admixtures can be cured at temperatures below freezing without harming its performance compared to that of concrete without the antifreeze admixture and cured at normal temperatures.

(1) Composition. Antifreeze admixtures are similar in composition to accelerating admixtures, but differences do exist. ACI 212.3R states that accelerating admixtures should not be used as antifreeze admixtures. However, some compounds used as the basis for nonchloride accelerating admixtures, such as sodium nitrite, calcium nitrite, and potassium carbonate, have been successfully used as antifreeze admixtures.

(2) Batching. Antifreeze admixtures are usually delivered in liquid form and should be added at the mixer with a portion of the mixing water at a dosage rate recommended by the manufacturer. They should be added to the concrete separately and not mixed with other admixtures, since adverse reactions may occur between admixtures which can decrease their effectiveness.

(3) Effect on strength. When antifreeze admixtures are used, early-age compressive strengths are usually significantly lower than when the admixture is not used and the concrete is cured at normal temperatures. The strength gain of concrete which contains an antifreeze admixture and is cured at temperatures below freezing proceeds at a slower rate than concrete which does not contain the admixture and is cured at temperatures above freezing. However, the strengths of two such concretes may be comparable at later ages.

(4) Effect on resistance to freezing and thawing. There is little published documentation describing the frost

resistance of concrete made with antifreeze admixtures; however, there is evidence that entrained air bubbles are less stable when antifreeze admixtures are used. Therefore, these admixtures should not be used unless acceptable frost resistance has been verified according to provisions of ASTM C 494 (CRD-C 87).

(5) Use with reactive aggregates. When sodium nitrite and potassium carbonate go into solution, if the nitrite or carbonate ions precipitate out, the sodium or potassium ions will associate with hydroxide ions to raise the pH of the pore fluid. Therefore, antifreeze admixtures containing these materials should not be used with reactive siliceous aggregates. Concrete made with these materials has also weakened after repeated exposure to cycles of wetting and drying. Therefore, antifreeze admixtures containing sodium nitrite or potassium carbonate should not be used in a marine environment.

(6) Corrosion of steel. Antifreeze admixtures made from nonchloride compounds have shown no tendency to cause corrosion of embedded reinforcing steel. Sodium nitrite and calcium nitrite reduce corrosion when used in proper amounts.

(7) Cost benefits. The use of an antifreeze admixture in concrete can be cost effective. The cost of concreting in very cold weather may be as much as 50 to 100 percent higher than that under normal conditions due to increased equipment and labor costs. The cost of antifreeze admixtures may be competitive with the higher costs associated with concreting during subfreezing temperatures.